Using Landsat 7 ETM+ imagery and Digital Terrain Models for mapping glacial lineaments on former ice sheet beds

Glasser, Neil F.; Jansson, Krister N.

Published in:
International Journal of Remote Sensing

DOI:
10.1080/01431160500106900

Publication date:
2005

Citation for published version (APA):
Glasser, N. F., & Jansson, K. N. (2005). Using Landsat 7 ETM+ imagery and Digital Terrain Models for mapping glacial lineaments on former ice sheet beds. *International Journal of Remote Sensing*, *26*(18), 3931-3941. https://doi.org/10.1080/01431160500106900

Using Landsat 7 ETM+ imagery and Digital Terrain Models for mapping glacial lineaments on former ice sheet beds

Krister N. Jansson and Neil F. Glasser

In this paper, we consider the application of Landsat 7 ETM+ imagery and Digital Terrain Models (DTM) for mapping glacial lineaments in a formerly glaciated area of Wales. A series of landform interpretation experiments were conducted using different false colour composites (FCC) and a DTM, both individually and in combination. The experiments indicate that the optimal FCC for detection of glacial lineaments at this scale includes the thermal-infrared (TIR) band. However, by performing the interpretation both in the TIR composite and in a visible and near-infrared (VNIR, bands 4, 3, and 2) draped over the DTM, we were able to substantially increase the number of lineaments identified. The glacial lineaments consist of fractured bedrock and are defined as rock drumlins. The landform system formed by these rock drumlins is characterized by convergent flow patterns at its head, attenuated lineaments, and abrupt lateral margins, which may indicate formation by fast-flowing ice.

1. Introduction

A variety of remotely sensed data have been used for mapping the geomorphology of formerly glaciated areas, including Landsat Thematic Mapper (TM) (McCabe *et al*. 1999, Clark and Stokes 2001, Stokes 2002), Landsat Multispectral Scanner (MSS) (Boulton and Clark 1990, Clark 1994, Clark and Stokes 2001, Jansson *et al*. 2003), SPOT HRV (Smith *et al*. 2000), Landsat 7 Enhanced Thematic Mapper Plus (ETM+) (Stokes and Clark 2003, Jansson and Glasser 2005), and ERS Synthetic Aperture Radar (SAR) (Clark *et al*. 2000, Clark and Stokes 2001). For a complete review of satellite imagery and geomorphological mapping, see Clark (1997). Linear landforms formed parallel to former ice-flow directions (cf. Menzies 1996) are often the most frequent and prominent feature of glacial landscapes. Based on their shape and size, they are usually classified as flutes, megaflutes, drumlins (drumlinoids and rock drumlins), megadrumlins or giant glacial grooves (Fairchild 1907, Linton 1963, Sugden and John 1976, Clark 1993, Benn and Evans 1998, Stokes and Clark 2003). The spatial distribution of subglacial landforms has been used as input data for reconstructions of former ice sheet configurations and subglacial thermal regimes (e.g. Boulton and Clark 1990, Kleman *et al*. 1994, 1997, McCabe *et al*. 1999, Clark *et al*. 2000, Jansson *et al*. 2002). Such reconstructions are recognized to be vital for the understanding of former ice sheet dynamics and their interactions with climate.

Mega flutes and giant glacial grooves 10–20km in length (Clark 1993, Stokes and Clark 2003) and drumlins 200m in height and of several kilometres in length (Jansson and Kleman 1999) protrude as prominent features on low-spatial resolution satellite images of areas such as the Canadian Shield and are well suited for geomorphological mapping purposes. The use of high-resolution Digital Terrain Models (DTM) to create glacial bedform topography images by simulated solar shading has also proved successful in detecting glacial lineaments (Clark 1997, Clark and Meehan 2001).

This paper describes a series of experiments with the overall aim of identifying discrete glacial lineaments in north-east Wales (figure 1), a formerly glaciated area now used to a large extent for agricultural purposes. We present the results of geomorphological mapping using different FCC of a subscene of a Landsat 7 ETM+ and a DTM. By using a VNIR colour composite draped over a shaded relief map constructed from the DTM, we were able to increase the number of glacial lineaments identified in the subscenes. Using these data, we explore the landform shaping processes involved in the formation of the glacial lineaments in this area of Wales. The term 'glacial lineaments' is used in this study in the same manner as Clark (1997), i.e. for subglacially streamlined features such as drumlins, rock drumlins, crag-and-tails and flutes.

2. Data set

This study was carried out in order to determine the method that provides the best possible technique for compilation of regional-scale maps of glacial lineaments parallel to ice-flow direction in Wales and other comparable environments. To achieve this aim, we explored the use of a Landsat 7 ETM+ satellite image (acquired

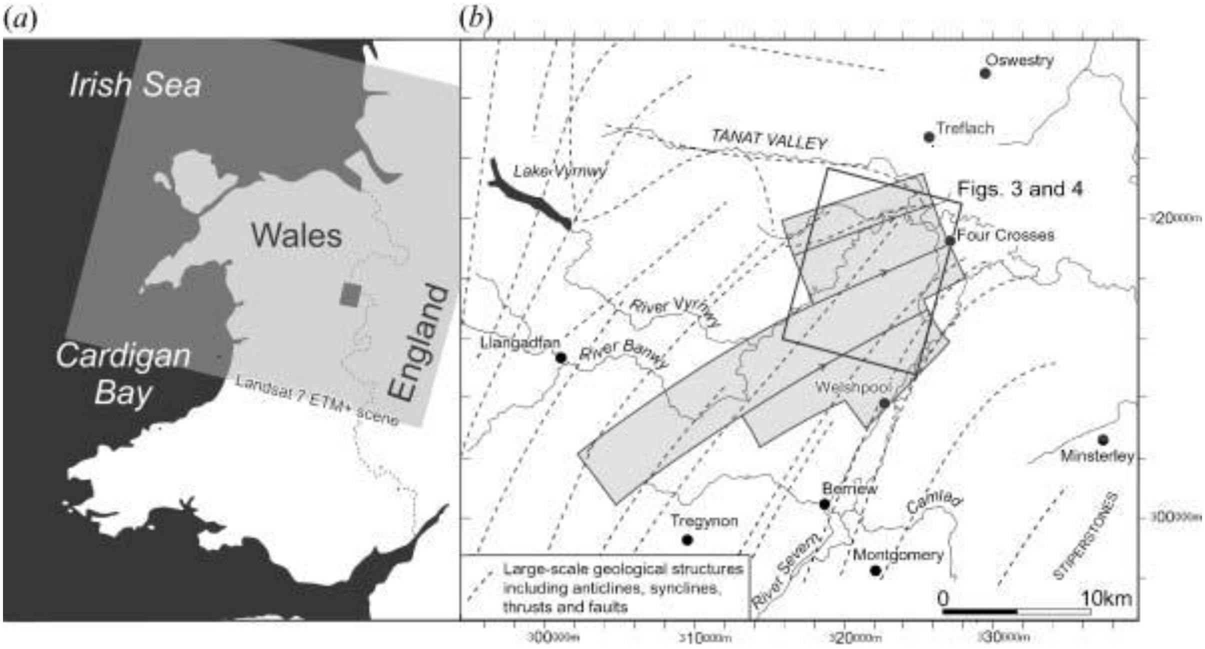

Figure 1. Location of the study area and localities mentioned in the text. (a) The grey box shows the area covered by the Landsat ETM+ scene and black box the area covered by the Landsat ETM+ subscene used in this study. (b) The majority of the identified rock drumlins form a well-defined landform system indicating ice flow towards the north-east (shown in grey with arrows indicating ice-flow direction). The box shows the outline of the subscene used. Large-scale geological structures are from Dunning (1992). The grid is in UK National Grid co-ordinates.

Table 1. Characteristics of the Landsat Enhanced Thematic Mapper Plus (ETM +) sensor system.

Subsystem	Band no.	Spectral range (μm)	Spatial resolution (m)
Visible	1	0.45–0.52	30
	2	0.53–0.61	30
	3	0.63–0.69	30
Near-IR	4	0.78–0.90	30
Mid-IR	5	1.55–1.75	30
	6	2.09–2.35	30
Thermal-IR	7	10.40–12.50	60
Panchromatic	8	0.52–0.90	15

10:59:07 on 26 March 2002, WRS reference 204/23, solar elevation 35.27º and solar azimuth 154.7º; table 1) covering northern Wales, in ENVI 3.6 image-processing software. To evaluate the potential of the data, we visually interpreted one 9.5612km subscene (figure 1) using the panchromatic band (band 8) and the following multi-band FCC images: (1) bands 4, 3, and 2 (VNIR composite), (2) bands 7, 4, and 2, and (3) bands 4, 5 and 6 ((tables 1 and 2) all in the order red, green, and blue) and a DTM. These band combinations were selected after initial experiments concerning the suitability of different band combinations. A similar approach, using different band combinations, was pioneered by Punkari (1982) who used Landsat MSS images to identify glacial lineaments. The VNIR composite was also draped on a DTM for the same procedure.

The Ordnance Survey Land-Form PANORAMA^{TM} DTM, sourced from EDINA Digimap (http://edina.ac.uk/digimap/index.shtml), has a horizontal resolution of 50m and a vertical resolution of <3m.

2.1 Experiments

Successful identification of landforms in remotely sensed images depends to a large extent on the ability and experience of the observer (cf. Smith *et al*. 2001). Observer bias in the interpretation of glacial lineaments is therefore inevitable. In order to minimize this bias, our study was performed by a single operator. One problem, however, with using a single operator is that ‘guided learning’ can be introduced from previous experiments. To reduce these effects, our different experiments were time-separated. Although inherited knowledge effects will therefore exist, we argue that the single operator approach provides a more reliable result than experiments using several operators, where different results are generated depending on the ability and experience of the operator. Since there is no published method for automated mapping of glacial lineaments, the single operator approach has the best prospect of success.

Table 2. Landsat ETM+ band–colour combinations used in this study.

Figure	ETM + band – colour assignment in composite		
	Red	**Green**	**Blue**
3(*b*)	4	5	6
3(*c*)	4	3	2
*	7	4	2

For results of interpretation, see table 3.
*Colour composite not shown in paper.

The DTM was used to create a shaded surface map with a *z*-scale factor of 1 and by simulating shading effects for low incoming solar radiation from the north-west. The general trend of glacial lineaments in the image is towards the ENE and NNE; therefore, incoming illumination from NW (cf. Lidmar-Bergström *et al*. 1991) was used to avoid azimuth biasing effects (Howard and Larsen 1972, Smith *et al*. 2001). Multiple illumination azimuths were also tested to prevent azimuth-biasing effects (Smith *et al*. 2001). High (45º) and low (20º) solar elevation images were tested. In agreement with Howard *et al*. (1972) and Smith *et al*. (2001) we found that a low-angle image was most suitable for detecting lineaments and glacial lineaments, respectively. Therefore, we used a shaded surface map with a solar elevation at 20º throughout this study. In this study we assume that it is theoretically possible to detect all glacial lineaments in all tested images together.

Experiments with contrast stretching and histogram equalization were performed on sub-scenes of the Landsat 7 ETM+ image to improve the landform signal strength. We also applied a high-pass filter to the panchromatic sub-scene, but this failed to resolve more subtle features.

3. Landforms and landscape

The study area is a gently undulating landscape comprising wide, shallow valleys and numerous streamlined hills (the glacial lineaments). Relative relief is low, with topographic high and low points of 380m and 60m above sea level, respectively. Bedrock is close to the surface over much of the area, and exposures on the flanks and upper surfaces of the streamlined hills show that these features are composed of solid bedrock, fractured bedrock and a thin soil cover (figure 2). Since the glacial lineaments in the study area consist of bedrock covered only by a thin layer of sediment, we choose to define them as rock drumlins.

4. Results

Figure 3 shows examples of data used for the interpretation of glacial lineaments in the area north of Welshpool (figure 1) and the interpretation of individual subscenes from the Landsat 7 ETM+ image and the DTM. The results show that the number of identified individual glacial lineaments changes with the use of different band combinations and especially in combination with the DTM (figure 3 and table 3). For example, 40 individual lineaments (29% of the total) were recognized on the DTM alone, but this figure increases as different FCCs are overlaid on the DTM. Bands 4, 5 and 6 (near-IR, mid-IR and thermal-IR, respectively) better suit the task than band combinations 7, 4 and 2 and 4, 3 and 2 (table 3). The VNIR FCC (bands 4, 3 and 2) draped on a DTM produced the best results (95 individual lineaments or 69% of the total) as it generates a more homogenous image compared with the infrared colour FCC (bands 4, 5 and 6), which in the study area generates a more fragmented image.

The colour combination and shading generated by draping the FCC (bands 4, 5 and 6) on a DTM does not permit successful identification of glacial lineaments in the study area. The panchromatic band allows only the identification of prominent lineaments (figure 4). Surprisingly, even though it has a higher spatial resolution (15 m), the panchromatic band only resolves 13 individual lineaments (9% of the total).

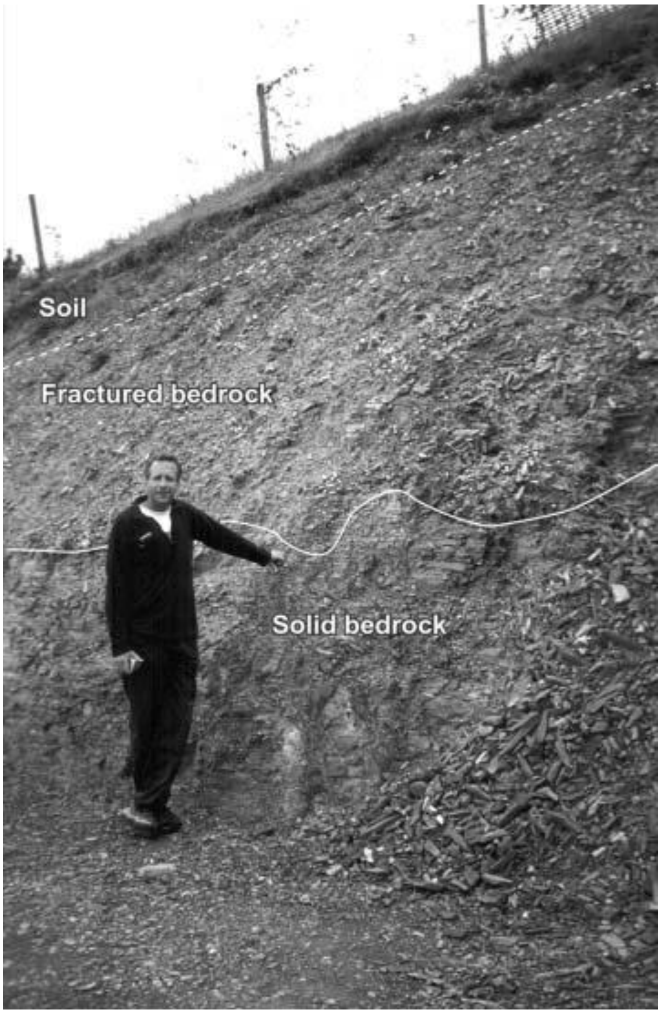

Figure 2. Internal composition of one of the rock drumlins in the study area, showing the transition from solid bedrock to fractured bedrock and finally into a thin soil cover. The total height of the section is approximately 4m.

False-colour composites (FCC) of Landsat 7 ETM+ images are well suited to the task of identifying and mapping faintly inscribed glacial lineaments such as flutes and larger features such as drumlins.

5. Implications for the identification of glacial lineaments

A successful visual interpretation of satellite images and aerial photography depends to a large extent on the experience of the interpreter and to what extent it is possible to identify a different signal from the landform compared with background terrain (cf. Clark and Meehan 2001). Landforms such as mega-flutes and weakly inscribed flutes are often relatively uncomplicated to detect in satellite images because of a clear response pattern present in the image (e.g. Stokes and Clark 2003). This pattern or surface structure often originates from the difference in water content of the soil and vegetation between the ridge crest of a flute and the inter-flute zone (Punkari 1982, Clark 1997). The lack of lake basins in the study area, however, complicates the interpretation of flutes as lake-basin orientation in debris-covered terrain is often governed by the ice-flow direction (Clark 1993, Stokes 2002).

Table 3. Results from the interpretation of glacial lineaments in the different data sets used in this study.

Type of data		Illustration	No. of glacial lineaments identified			Proportion of total glacial lineaments (%)	
DTM							
1	Shaded relief image	Figure 3 (*a*)	40[1]			29	
Landsat 7 ETM +							
2	Panchromatic band	Figure 4	13			9	
3	Colour composite (bands 7,4 and 2)	–	31	∑=60[2]	∑=127	22	43
4	Colour composite (bands 4,3 and 2)	–	34			25	
5	Colour composite (bands 4, 5 and 6)	Figure 3 (*b*)	49			36	
6	Colour composite (bands 4, 3 and 2) draped on DTM (shaded relief image)	Figure 3 (*c*)	95[3]			69	
	Total identified glacial lineations		∑=138			100	

The different colour composite subscenes were extracted from a Landsat 7 ETM+ satellite image covering northern Wales, and the DTM was generated from The Land-Form PANORAMA™ DTM, sourced from EDINA Digimap.
[1]11 of the glacial lineaments were identified only in the shaded relief image.
[2]The majority of lineaments were identified in the three colour composites.
[3]Twenty-eight were also identified in the colour composite.

Drumlins and inter-drumlin areas often display similar surface cover, which means that drumlins and inter-drumlin areas have a similar spectral signature in visible and near- and mid-infrared. Similar problems were detected by Clark (1997), who identified the need for imagery with a low-angle illuminating source to better produce a signal that highlights slope angles (see Slaney 1981). High-resolution DTMs provide a means of creating relief maps with simulated solar shading, and it has been suggested that these DTMs are superior to satellite images for mapping of geomorphological features (Clark 1997, Clark and Meehan 2001). Shaded relief images from DTMs (25m grid resolution) have been successfully applied to geomorphological mapping of drumlins and ribbed moraine in Ireland (Clark and Meehan 2001). In this study, however, the DTM alone resolved only 29% of the total number of identified glacial lineaments. The relatively poor performance of the DTM is probably caused by the relatively low relief in the study area. A higher resolution DTM would most probably have made it easier to identify glacial lineaments in the study area. The results from the interpretation of the DTM are, however, three times better (table 3) compared with the results from using the panchromatic subscene. The poor performance using the panchromatic image is difficult to understand. We suggest that the difficulties in identifying glacial lineaments using the panchromatic band are caused by the ability of the human eye to separate many different grey levels, which, in an area highly fragmentized by land use, generate a complex image with a hidden landform signal.

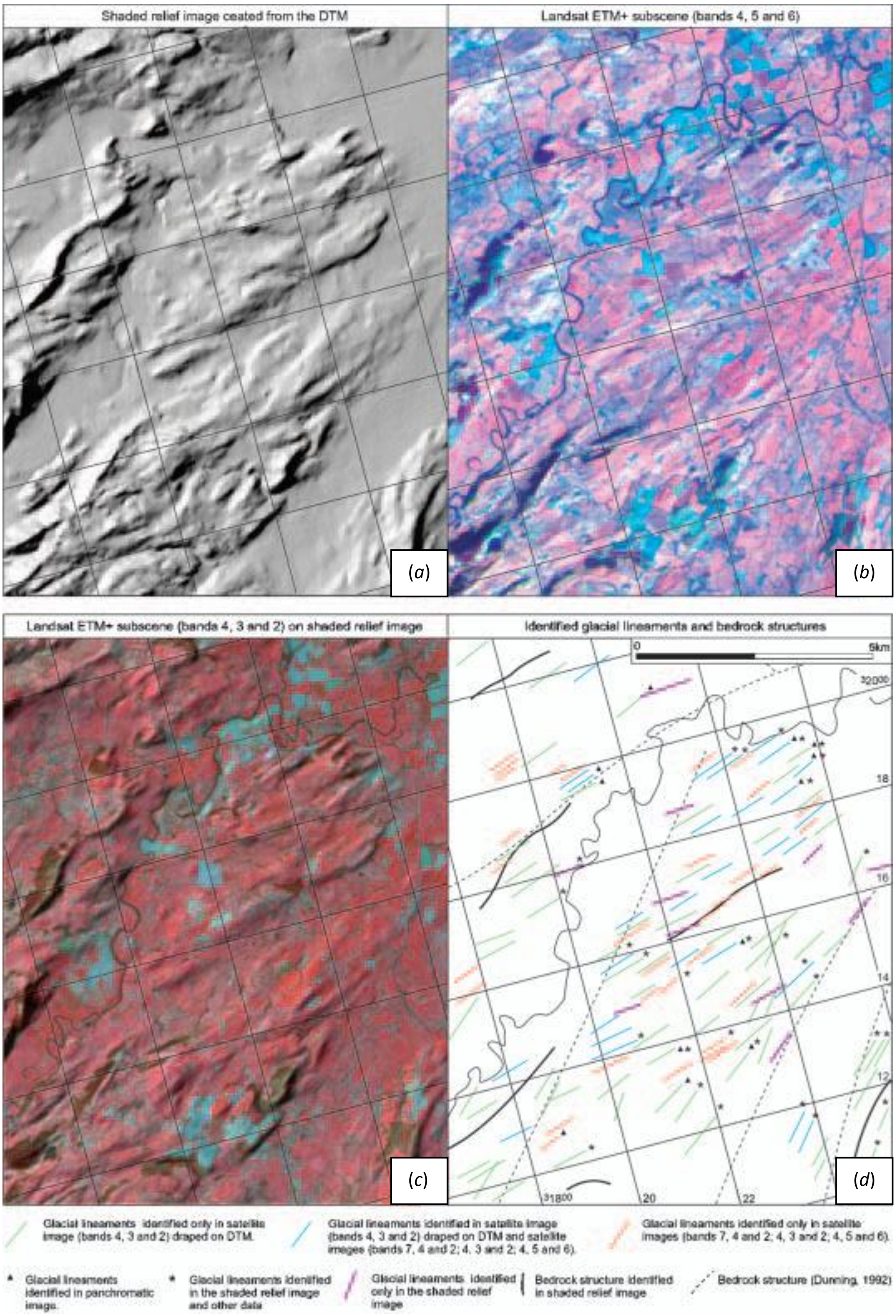

Figure 3. Examples of data used in the interpretation of glacial lineaments. Contrast stretches have been applied on satellite images. Bedrock structures were separated from glacial lineaments by their higher grade of continuity and an occurrence as a winding pattern. For location, see figure 1. (a) Shaded relief image constructed from the DTM (50m spatial resolution) with a simulated shading effect from low incoming solar radiation from the northwest. © Crown Copyright Ordnance Survey. An EDINA Digimap/JISC supplied service. (b) Infrared composite of a Landsat ETM+ scene (bands 4, 5 and 6). (c) Colour infrared composite of a Landsat ETM+ scene (bands 4, 3 and 2) draped on a shaded relief image. © Crown Copyright Ordnance Survey. An EDINA Digimap/JISC supplied service.

(d) Combined results from the landform interpretation. Identified rock drumlins are characterized by a high elongation ratio and parallel conformity, and together they form a landform system defined by well-defined lateral borders. For details, see table 3.

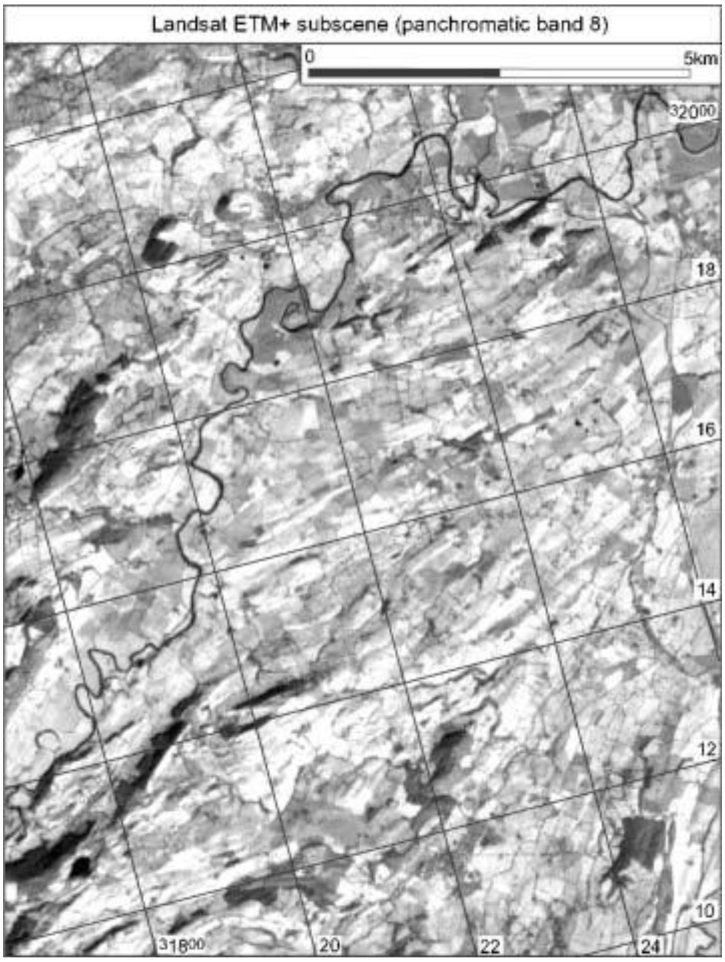

Figure 4. Panchromatic image of the Landsat 7 ETM+ sub-scene (band 8). Contrast stretches have been applied to satellite images. Compare with figure 3. For location, see figure 1.

Thermal-IR (TIR) imagery has successfully been used for determining rock type and structures, and mapping soil type and soil moisture (Lillesand and Kiefer 1994). We suggest that, compared with inter-rock drumlin areas, the rock drumlins are characterized by more fractured bedrock in the uppermost layer (figure 2) and were possibly created during the land-forming processes. The fractured bedrock in the rock drumlins may cause different soil moisture and the development of a different soil within the rock drumlins compared with the inter-rock drumlin areas. This may explain the benefit of using a colour composite including the TIR band. On the other hand, using a Landsat 7 ETM+ VNIR FCC (bands 4, 3 and 2) draped over a DTM gives the topographical association needed for the interpreter to be able to successfully identify larger rock drumlins as well as more subtle glacial lineaments. Therefore, to obtain the best possible results when mapping glacial lineaments in Wales or other comparable areas, we recommend the use of Landsat 7 ETM+ band 4, 3 and 2 draped on a DTM in combination with a Landsat 7 ETM+ FCC showing bands 4, 5 and 6. The use of the DTM allowed us to identify 11 glacial lineaments not detected in other images, which makes the DTM a viable alternative or complement to the sub-scene showing band combination 4, 5 and 6. One limitation of using Landsat ETM+ is that an on-board satellite failure means that no new scenes will be acquired in the future. However, since numerous Landsat ETM+ scenes already exist for this and other formerly glaciated areas, this is not a serious limitation.

6. Landform formation and ice-sheet dynamics

Rock drumlins have been described from several other glaciated areas, for example in Scotland (Linton 1963, Gordon 1981), Scandinavia (Svensson and Frisén 1964, Rudberg 1973), and North America (Fairchild 1907, Aronow 1959, Dionne 1984, Evans 1996). The form and characteristics of landforms associated with ice-scoured terrain depend to a large extent on bedrock structure (Gordon 1981). The rock drumlins identified in Wales, in general, follow the trend of the bedrock structure in the area (figure 3(d)). The streamlined nature and 'drumlin-morphology' of the features and the parallel conformity within individual lineaments clearly indicate glacial erosion to be the land-forming process, although of course the bedrock structure governs to a great extent the morphology of individual rock drumlins.

Streamlined bedrock forms (rock drumlins, whalebacks and roches moutonnées) form under different sub-glacial conditions (Evans 1996). Individual rock drumlins in north-east Wales often exceed 30m in height, which implies thousands of years for formation assuming erosion rates of mm a21. Hindmarsh (1999) suggested that high ice-flow velocity will govern high growth rates of glacially streamlined features. This is in line with the suggestion of Evans (1996) that thick and fast flowing ice is required to create streamlined bedrock features dominated by bedrock abrasion and not by bedrock plucking, which instead forms roches moutonnées.

We speculate that the rock drumlins (glacially streamlined remnants of a former bedrock cover) in this study area were formed by a combination of glacial erosion of a pre-existing highly fractured or weathered bedrock cover and enhanced glacial erosion due to fast flowing ice. The rock drumlins in the study area are part of a larger landform system (Jansson and Glasser 2005) that meets the criteria proposed by Stokes and Clark (1999) for palaeo-ice streams (convergent flow patterns at its head, attenuated lineaments, and abrupt lateral margins), although these postulated ice streams are somewhat smaller than other published examples.

7. Conclusion

Previous suggestions that panchromatic images and DTMs are the most suitable for the identification of glacial lineaments in satellite image data (Clark 1997, Clark and Meehan 2001) are not confirmed by this study. By employing the commonly used VNIR FCC (bands 4, 3 and 2) we only identified 34 individual glacial lineaments (25% of the total) in our study area. However, the use of a FCC Landsat 7 ETM+ scene (bands 4, 3 and 2) draped over a shaded relief image is a successful means of identifying and mapping glacial lineaments (69% of the total identified glacial lineaments). By combining this data set with the FCC including the TIR band, it is possible to increase the number of identified glacial lineaments by 21 (15%) or by using the shaded relief image by 11 (8%). Using the suggested method, we were able to identify a total of 138 rock drumlins in the subscene covering an area of north-eastern Wales.

Acknowledgement

This work was funded by grants from the Royal Physiographic Society in Lund to Krister N. Jansson. We also wish to thank Göran Alm at the Department of Physical Geography and Earth Sciences, University of Wales, Aberystwyth for constructive comments on the manuscript. We are grateful to anonymous referees for their helpful comments that improved this paper.

References

ARONOW, S., 1959, Drumlins and related streamline features in the Warwick-Tokio area, North Dakota. *American Journal of Science*, 257, pp. 191–203.

BENN, D.I. and EVANS, D.J.A., 1998, *Glaciers and Glaciation* (London: Arnold).

BOULTON, G.S. and CLARK, C.D., 1990, A highly mobile Laurentide ice sheet revealed by satellite images of glacial lineations. *Nature*, 346, pp. 813–817.

CLARK, C.D., 1993, Mega-scale glacial lineations and cross-cutting ice-flow landforms. *Earth Surface Processes and Landforms*, 18, pp. 1–29.

CLARK, C.D., 1994, Large-scale ice-moulding: a discussion of genesis and glaciological significance. *Sedimentary Geology*, 91, pp. 253–268.

CLARK, C.D., 1997, Reconstructing the evolutionary dynamics of former ice sheets using multi-temporal evidence, remote sensing and GIS. *Quaternary Science Reviews*, 16, pp. 1067–1092.

CLARK, C.D., KNIGHT, J.K. and GRAY, J.T., 2000, Geomorphological reconstruction of the Labrador sector of the Laurentide Ice Sheet. *Quaternary Science Reviews*, 19, pp. 1343–1366.

CLARK, C.D. and MEEHAN, R.T., 2001, Subglacial bedform geomorphology of the Irish Ice Sheet reveals major configuration changes during growth and decay. *Journal of Quaternary Science*, 16, pp. 483–496.

CLARK, C.D. and STOKES, C.R., 2001, Extent and basal characteristics of the M’Clintock Channel Ice Stream. *Quaternary International*, 86, pp. 81–101.

DIONNE, J-C., 1984, Le rocher profile: une forme d’erosion glaciaire negligee. *Géographie Physique et Quaternaire*, 38, pp. 69–74.

DUNNING, F.W., 1992, Structure. In *Geology of England and Wales*, P.McL.D. Duff and A.J. Smith (Eds) (London: The Geological Society), pp. 523–561.

EVANS, I.S., 1996, Abraded rock landforms (whalebacks) developed under ice streams in mountain areas. *Annals of Glaciology*, 22, pp. 9–16.

FAIRCHILD, H.L., 1907, Drumlins of central New York. *New York State Museum Bulletin*, 111, pp. 391–443.

GORDON, J.E., 1981, Ice-scoured topography and its relationships to bedrock structure and ice movement in parts of northern Scotland and West Greenland. *Geografiska Annaler*, 63A, pp. 55–65.

HINDMARSH, R.C.A., 1999, Coupled ice-till dynamics and the seeding of drumlins and bedrock forms. *Annals of Glaciology*, 28, pp. 221–230.

HOWARD, K.A. and LARSEN, B.R., 1972, Lineaments that are artifacts of lighting. In *Apollo 15 Preliminary Science Report* (Washington, DC: US National Aeronautics and Space Administration), pp. 25–58–25–62.

JANSSON, K.N. and GLASSER, N.F., 2005, Palaeoglaciology of the Welsh sector of the British–Irish Ice Sheet. *Journal of the Geological Society*, London, 162, pp. 25–38.

JANSSON, K.N. and KLEMAN, J., 1999, The horned crag-and-tails of the Ungava Bay landform. swarm, Québec-Labrador, Canada. *Annals of Glaciology*, 28, pp. 168–174.

JANSSON, K.N., KLEMAN, J. and MARCHANT, D.R., 2002, The succession of ice-flow patterns in north-central Québec-Labrador. Canada. *Quaternary Science Reviews*, 21, pp. 503–523.

JANSSON, K.N., STROEVEN, A.P. and KLEMAN, J., 2003, Configuration and timing of Ungava Bay ice streams, Labrador-Ungava, Canada. *Boreas*, 32, pp. 256–262.

KLEMAN, J., BORGSTRÖM, I. and HÄTTESTRAND, C., 1994, Evidence for a relict glacial landscape in Québec-Labrador. *Palaeogeography, Palaeoclimatology, Palaeoecology*, 111, pp. 217–228.

KLEMAN, J., HÄTTESTRAND, C., BORGSTRO¨M, I. and STROEVEN, A., 1997, Fennoscandian palaeoglaciology reconstructed using a glacial geological inversion model. *Journal of Glaciology*, 43, pp. 283–300.

LIDMAR-BERGSTRO¨M, K., ELVHAGE, C. and RINGBERG, B., 1991, Landforms in Skåne, south Sweden. *Geografiska Annaler*, 73A, pp. 61–91.

LILLESAND, T.M. and KIEFER, R.W., 1994, *Remote Sensing and Image Interpretation*, 3rd ed. (New York: Wiley).

LINTON, D.L., 1963, The forms of glacial erosion. *Transactions of the Institute of British Geographers*, 33, pp. 1–28.

MCCABE, A.M., KNIGHT, J. and MCCARRON, S.G., 1999, Ice-flow stages and glacial bedforms in north central Ireland: a record of rapid environmental change during the last glacial termination. *Journal of Geological Society, London*, 156, pp. 63–72.

MENZIES, J. and SHILTS, W.W., 1996, Subglacial environments. In *Past Glacial Environments: sediments, forms and techniques*, J. Menzies (Ed.), pp. 15–136 (Oxford: Butterworth-Heinemann).

PUNKARI, M., 1982, Glacial geomorphology and dynamics in the eastern parts of the Baltic Shield interpreted using landsat imagery. *Photogrammetric Journal Finland*, 9, pp. 77–93.

RUDBERG, S.R., 1973, Glacial erosion forms of medium size—a discussion based on four Swedish case studies. *Zeitschrift für Geomorphologie* N.F, Suppl. Bd. 17, pp. 33–48.

SLANEY, V.R., 1981, Landsat images of Canada. A geological appraisal. *Geological Survey of Canada Paper*, 80-5, p. 102.

SMITH, M.J., CLARK, C.D. and WISE, S.M., 2001, Mapping glacial lineaments from satellite imagery: an assessment of the problems and development of best procedure. *Slovak Geological Magazine*, 7, pp. 263–274.

SMITH, G.R., WOODWARD, J.C., HEYWOOD, D.I. and GIBBARD, P.L., 2000, Interpreting Pleistocene glacial features from SPOT HRV data using fuzzy techniques. *Computer and Geosciences*, 26, pp. 479–490.

STOKES, C.R., 2002, Identification and mapping of palaeo-ice stream geomorphology from satellite imagery: implications for ice stream functioning and ice sheet dynamics. *International Journal of Remote Sensing*, 23, pp. 1557–1563.

STOKES, C.R. and CLARK, C.D., 1999, Geomorphological criteria for identifying Pleistocene ice streams. *Annals of Glaciology*, 28, pp. 67–74.

STOKES, C.R. and CLARK, C.D., 2003, Giant glacial grooves detected on Landsat ETM+ satellite imagery. *International Journal of Remote Sensing*, 24, pp. 905–910.

SUGDEN, D.E. and JOHN, B., 1976, *Glaciers and Landscape* (London: Edward Arnold).

SVENSSON, H. and FRISÉN, R., 1964, Hällmorfologi och isrörelser inom ett alvarområde vid Degerhamn. Geografisk Årsbok, 40, pp. 19–30.